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AIR FORCE

HUMAN RESOURCES

ATTENTION EFFECTS ON FORM DISCRIMINATION AT DIFFERENT ECCENTRICITIES

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Considerable disagreement exists in the visual attention literature about how attention is allocated over the visual field. One frequently expressed metaphor is that attention moves like a spotlight and, thus, would take longer to shift to targets further from fixation. In order to test this metaphor, five experiments were conducted in which target location was precued and form discrimination accuracy was assessed. By varying the interval between the precue and the target (stimulus onset asynchrony, SOA), a time course of attention effects was obtained for targets at 2°, 6°, and 10° eccentricity. In the first three experiments, precuing effects were found, but there were no differences in performance as a function of eccentricity for very short SOAs, with either a peripheral cue or a foveal arrow cue. For long SOAs, however, performance was better for targets that were closer to fixation. In Experiments 4 (peripheral cue) and 5 (foveal cue), the targets were scaled to make them equally discriminable at all eccentricities. Again precuing effects were found, but there were no differences in accuracy as a function of eccentricity for most SOAs. These results suggest that attention shifting is not analogous to a moving spotlight.

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SUMMARY

Recent research has verified the fact that perception of visual stimuli is facilitated by attention directed towards the stimulus without eye movement. However, there has been little agreement as to how attention is allocated in visual space. One suggestion is that attention moves through space like a spotlight, improving visibility as the beam moves across space. This metaphor implies that time to shift the focus of attention will increase in proportion to the distance that attention has to move. This hypothesis was tested in five experiments in which attention was directed with a precue to indicate where the target would appear. Discrimination of T-like characters was facilitated as time between the precue and the target increased. However, distance of the targets from fixation (2^{o}, 6^{o}, and 10^{o}) had no effect on the time for attention to facilitate discrimination, provided that the characters were sized so as to be equally visible at each location. These data suggest that it did not take attention longer to move 10^{o} than it did to move 2^{o}. Thus, the spotlight metaphor for the movement of attention was not supported.

PREFACE

This report represents a portion of the research program accomplished under Project 2313; Task 2313T3, Perceptual and Cognitive Dimensions of Pilot Training, Dr. Elizabeth L. Martin, Task Scientist. The division has an ongoing basic (6.1) research program in visual attention to provide knowledge needed in order to understand attention to the visual scene. This knowledge is of benefit to the AFHRL/OT 6.2 and 6.3 R&D programs, which are dedicated to the development and evaluation of visual systems for use in flight simulators.

These studies were conducted by Dr. Cheal while on an Air Force Systems Command University Resident Research Program Fellowship. Sincere appreciation is expressed to C. Voltz for computer programming.

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I. INTRODUCTION

Recent interest in visual attention has led to extensive discussion of how attention is allocated in space. A common metaphor likens attention to a spotlight that can illuminate a particular part of the visual field. This attentional beam moves through visual space in an analog fashion; that is, there is an increase in the amount of time needed for attention to move as the distance it is to be moved increases (Posner, Snyder, & Davidson, 1980; Shulman, Remington, & McLean, 1979; Tsal, 1983).

Some existing research appears to support this metaphor and some does not. In this report, we first review briefly the methods and results of research on this issue. We then describe a method for measuring attention effects that we believe allows an adequate test of the moving spotlight metaphor. Finally, we present five experiments using this method that provide evidence against the spotlight theory of attention movement. These experimental results are discussed in relation to other viable theories of attentional allocation.

Support for a Spotlight Theory of Attention

Shulman et al. (1979) concluded that their data, from a luminance increment detection task, supported a moving spotlight model. Observers detected a change in intensity of a light-emitting diode (LED) that was either 18° right or left of fixation. A foveal arrow cue directed the observer to attend to the right or left. On 70% of the trials, this cue was valid; that is, it correctly indicated the location of the LED. On the invalid trials (those that were incorrectly cued), one of three events could occur: The opposite LED at 18° could brighten (10% of the trials); or an LED at 9° on the right (10% of the trials) or on the left (10% of the trials) could brighten. The interval between the presentation of the cue and the brightening of the LED (the cue-target stimulus onset asynchrony, SOA) was varied. The key finding was that, for intermediate SOAs, observers responded more quickly to a 9° target on the cued side than to the 18° target even though the 18° target was precued. The implication was that, for these SOAs, the 9° LED was brightened just as the attentional spotlight passed over it, thus resulting in rapid responses. However, a potential problem was that responses were as rapid to a 9° target on the uncued side as to the cued target, for SOAs less than 300 msec.

Tsal (1983) also investigated this issue and concluded that attention moved through visual space with a constant velocity of approximately 8 msec per degree. He found that it took longer for observers to respond to targets that were further from fixation. In his research, a letter discrimination was used, but the letters were the same size at all eccentricities. Thus, longer reaction times (RTs) at greater eccentricities could have been due to the fact that acuity is poorer with increased distance from fixation (e.g., Anstis, 1974). Tsal recognized this problem in his second experiment. However, the control, which was to compare discriminations that differed in difficulty (D vs. O compared to C vs. X), may not have been adequate. These studies have received detailed criticisms previously (Eriksen & Murphy, 1987; Yantis, 1988).

Evidence Against a Spotlight Theory of Attention

Other research findings have not supported the concept that the time to shift attention is dependent on the distance to be moved. For instance, Remington and Pierce (1984) found no evidence for fixed-velocity, analog attention shifts. They suggested that movement of attention is more similar to hand movements or to saccadic eye-movements where velocity is proportional to distance; i.e., time-invariant movement rather than fixed velocity movement. Their conclusions were based on small differences in RT on trials that were invalid when attention was misdirected 4^{o} away from the target compared to those trials in which attention was misdirected 20^{o} away from the target. On valid trials, RT was shorter when the stimulus was closer to fixation.

Shulman, Wilson, and Sheehy (1985) found that an attentional gradient that extended outward from the center of the attentional focus was a better descriptor of their results than a fixed-velocity movement. Although RT increased as the distance from the focus of attention increased, the effect of a probe to an uncued location, varying in distances of 0.5^{o} to 12^{o} from the cued location, was smaller when attention was focused in the periphery than when it was in more medial positions. In these experiments, the intensity of target lights at different eccentricities was adjusted for equal brightness by each observer. However, as the authors point out, brightness may not be the critical variable. Rather, the important variable may be the area of the retina that is stimulated; i.e., the size of the target.

LaBerge and Brown (1986) indirectly varied target eccentricity in a study of attention allocation to groups of characters that varied in intercharacter spacing. They found that distance of the target from fixation was not systematically related to RT. Thus, they concluded that their data were not consistent with a constant-velocity shift of attention. To be consistent with their data, a spotlight theory would need to assume that the speed of the shift increased with increases in the size of the intercharacter spacing.

The data of Hughes and Zimba (1985) also were not suggestive of a fixed-velocity movement of attention, although their study was not designed to test this hypothesis. In their study, RT differences between valid and invalid cues in detecting onset of a probe light depended on whether the probe was in the same or the opposite hemifield as the foveal or peripheral precue. Similar results occurred at the vertical meridian and at the horizontal meridian (Hughes & Zimba, 1987). In these experiments, observers responded as quickly to probes in unexpected locations as to valid targets as long as the probe was in the same hemifield as the expected target, even when the probe was as much as 18^{o} from the cued location. If the probe was in the opposite hemifield, delayed responses typical of invalid trials were observed. If one assumes that attention moves to the cue and then moves to the probe or target, a moving spotlight interpretation predicts an effect that was not found; that is, it would take longer to move to probes that are greater distances from the cue even if both are in the same hemifield.

Rizzolatti, Riggio, Dascola, and Umilta (1987) also found a delay in responding when it was necessary for attention to cross a meridian, either horizontal or vertical. These authors concluded that neither the hypothesis that attention moved with a constant time nor the hypothesis that attention moved with a constant velocity was consistent with their data. They suggested that their data were consistent with the hypothesis of an attentional gradient (i.e., a fixed amount of attentional activity that is spread across the visual field), but that an adequate hypothesis needed to include the effect of increased delay as attention moved from one half of the visual field to the other.

Although the studies above argue against a fixed-velocity, analog movement of attention, only LaBerge and Brown (1986) used a discrimination task, and they did not use a typical location-cuing paradigm. In the other studies, a detection task was used. There are large differences between precuing effects on luminance increment detection and those found with character discrimination tasks (Müller & Findlay, 1987; Posner et al., 1980).

Recently, Murphy and Eriksen (1987) explored the issue of how attention moves through space. They used a precue to direct attention to a letter in a discrimination task. Even though discrimination reaction times increased with increasing eccentricities from 1^{o} to 3^{o}, and decreased with longer SOAs, there was no interaction between SOA and eccentricity as would be expected if the time to shift attention increased with increased distances. Therefore, these authors concluded that attention moved to a target as rapidly when the distance was 3 degrees as when it was only 1 degree. Also, they found no greater interference from a noise letter located between fixation and target than when the noise letter was located beyond fixation. In fact, the amount of interference from a noise letter depended on its distance from the target location and not upon its location relative to fixation.

Thus, these data suggest that attention may shift as rapidly to 3° as to 1°, but it is not known whether it takes longer to move attention to locations of greater eccentricity. The experiments reported in the present report include targets presented at locations up to 10° eccentricity.

Location-Cuing Paradigm

The present experiments, like most previous studies, use a location-cuing paradigm to elicit shifts of attention. In our version of this paradigm, a precue directs attention to one of four possible locations, equidistant from fixation (Cheal, Lyon, & Hubbard, 1987; Lyon, 1987). After a variable interval (0 or 16.7 msec to 268 msec), a stimulus appears at each location, followed by a mask. The observer then attempts to identify the target at the cued location. In previous work, using T-like targets, it was found that improvements in discrimination accuracy occurred very rapidly following the precue. Accuracy improved as SOA lengthened, until an asymptote was reached at an SOA of 100 to 150 msec. At longer SOAs, accuracy remained the same or decreased somewhat.

Directing attention in this way has some potential advantages. One advantage is that the early part of the time course of attention effects can be plotted because of the frequent sampling of short SOAs (at 16.7 msec intervals). In some of the experiments above (Rizzolatti et al., 1987; Shulman et al., 1985), the SOAs used were much longer. Long SOAs can cause the facilitatory effects of a cue to be replaced by inhibitory effects (Posner & Cohen, 1984; Posner, Rafal, Choate, & Vaughan, 1985; Tassinari, Aglioti, Chelazzi, Marzi, & Berlucchi, 1987). If the cue is very long, the same problem exists as with long SOAs; that is, attention may move elsewhere. A further advantage of using short SOAs is that most of the trials are completed before a saccade can be made to the target.

Using masked targets is another departure from most previous studies. The time course of attention effects is difficult to determine if the amount of time allowed for an attention shift is not limited. The interval between cue onset and target onset is typically considered to be the attention shifting time, but attention effects may continue to accumulate during target presentation as well (Lyon, 1987). When the target is presented until the observer responds, it is difficult to determine how much time was used for shift and focus of attention.

Furthermore, two different kinds of precues were used in the present experiments. Each has particular advantages. A cue presented near the peripheral target (peripheral cue) attracts or elicits attention more quickly than does an arrow presented at fixation (foveal cue) that directs attention toward the target location. The peripheral cue also specifies target eccentricity in advance, whereas the foveal cue does not. On the other hand, the foveal cue assures that attention is focused at fixation at the beginning of each trial. Furthermore, the visibility of the peripheral cue could vary with target eccentricity, whereas foveal cue visibility would not. In order to provide adequate controls for these various effects, a peripheral cue was used in some experiments and a foveal cue in others.

It was also necessary to consider the possibility of warning signal or general alerting effects of the cue (Eriksen & Murphy, 1987). Such effects should be minimal in the present paradigm. The interval between the onset of the fixation bar at the start of each trial and the onset of the cue (668 msec) was selected to maximize alertness prior to the cue (Niemi & Naatanen, 1981). In addition, SOA was randomized to provide more uncertainty as to the onset of the target; an accuracy measure rather than a reaction time measure was used to reduce the consequences of general alerting effects; and a discrimination rather than a detection was required (Niemi & Naatanen, 1981; Posner, Klein, Summers, & Buggie, 1973).

Moreover, in studies that have explicitly tested for warning signal effects in the location-cuing paradigm, the effects of a location-neutral cue have been found to be consistently smaller than the effects of a location cue (Bashinski & Bacharach, 1980; Briand & Klein, 1987; Colegate, Hoffman, & Eriksen, 1973; Eriksen & Hoffman, 1974; Eriksen & St. James, 1986; Eriksen & Yeh, 1985; Holtzman, Sidtis, Volpe, Wilson, & Gazzaniga, 1981; Jonides, 1980, 1983; Lambert & Hockey, 1986; McLean & Shulman, 1978; Parasnis & Samar, 1985; Posner & Boies, 1971; Posner et al., 1980; Tassinari et al., 1987; Van der Heijden, Wolters, Groep, & Hagenaar, 1987).

Predictions

It is possible to predict the results that would be obtained with this paradigm if attention requires more time to shift greater distances. First, assume that an increase in accuracy with longer SOAs reflects the increasing likelihood of attention having arrived at the target location prior to target onset. With increases in the eccentricity of the target, there should be increases in the time needed for attention to arrive at the target location. Thus, if the spotlight theory is correct, when SOAs are short, attention is less likely to have arrived at locations of greater eccentricity than those of lesser eccentricity; therefore, accuracy should decrease as eccentricity increases.

Data collected by Tsal (1983) can be used for quantitative predictions. Tsal found that asymptotic reaction time was reached with the following SOAs and eccentricities: 84 msec for 4°, 117 msec for 8°, and 150 msec for 12°; i.e., an increase of approximately 33 msec in SOA for each 4° eccentricity. Thus, Tsal's results suggest that a given increase in accuracy should require an additional 33 msec SOA for each additional 4° of target eccentricity. This would result in a lateral translation of the accuracy/SOA function to the right.

On the other hand, if time to move attention does not increase as the distance to the target increases, there should be no lateral translation of the accuracy/SOA function. In the present report, five experiments are reported that test whether or not attention "moves like a spotlight" when cued to a peripheral target location. The data suggest that the metaphor is inadequate.

II. EXPERIMENT 1

The first question to be answered was whether there would be a lateral translation of the accuracy/SOA function with increasing target eccentricity. Differences of 4° between target locations were used in order to test the quantitative prediction based on Tsal's data.

Method

Observers

Three right-handed women, 26 to 40 years of age, with normal or corrected to normal vision were paid to participate in 15 approximately 1-hour sessions. In addition to the hourly salary, two of the observers could earn a bonus based on overall accuracy for each stimulus set. The bonus was used to increase motivation for accuracy. The other observer was an employee of the laboratory. All observers had participated in visual attention experiments previously.

Apparatus

Stimuli were displayed by an IBM-XT on an enhanced color monitor with a luminance of 13.7 cd/m^2 (phosphors: P-22-B, P-22-G, and P-22-R, all with decay to 10% in less than 1 msec). An extended character set was generated in order to present the desired characters. Adjustable chin and head rests helped to maintain head position at a distance of approximately 37 cm from the display.

The short duration of stimulus presentation prevented any facilitation of responses by eye movement. In fact, an eye movement would have reduced response accuracy under some conditions because of saccadic suppression. However, in order to provide confirmation that fixation was maintained by the observer prior to responding, eye movement was monitored continuously with a video camera.

Stimuli

T-like figures were used as stimuli and targets. These were similar to those used previously (Cheal et al., 1987; Lyon, 1987). "Right" and "left" T-like stimuli were composed of a 0.5° line, consisting of 2 rows of 3 pixels each, that extended either right or left from the center of a 0.9° vertical line comprised of 1 column of 12 pixels (total number of pixels = 18). "Up" and "down" T-like stimuli were composed of a 0.5° line, consisting of one column of 5 pixels, that extended either up or down from a 0.9° horizontal line comprised of 2 rows of 7 pixels each (total number of pixels = 19; Figure 1). The white pixels were presented against a dark gray background.

Procedure

Observers were seated in front of the computer monitor with room lights illuminated. They were instructed to maintain fixation on a bar of light (0.2° X 0.4°) that remained in the center of the screen throughout each trial. The computer displayed frames of information at the rate of 60 per second. Thus, the duration of each frame was 16.7 msec.

After "START" appeared on the computer screen, the observer pressed a computer key to begin each block of trials. The fixation bar then appeared (Figure 1). After 668 msec, a square cue (0.8°) appeared in one of twelve possible locations (shown as x in Figure 1): centered at approximately 3°, 7°, or 11°, above, below, right or left of fixation. The duration of this cue was one frame (16.7 msec). The cue was followed by a screen that was blank except for the fixation bar. This interval varied from 0 to 250 msec. The sum of the cue duration and this variable interval was the cue-target SOA. Thirteen SOAs were randomized within blocks (16.7, 33, 50, 67, 84, 100, 117, 134, 150, 167, 200, 234, or 267 msec). At the end of the SOA, stimuli appeared at each of the four locations (above, below, right, and left of fixation) centered at approximately 2°, 6°, or 10°, dependent on whether the cue was 3°, 7°, or 11°, respectively. The target was the stimulus adjacent to the cued location.

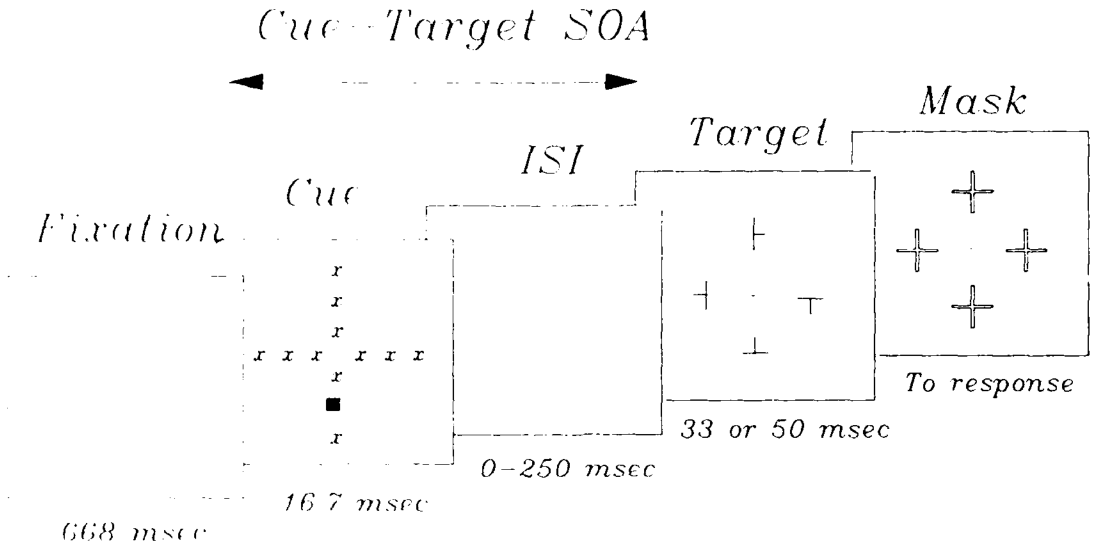

Figure 1. Stimulus events for trials. Sequence of stimulus screens for each trial in Experiment 1. Small 'x's in the second frame were not presented to observers, but were included in the figure in order to show the alternative locations for the cue. ISI, interstimulus interval.

Stimuli were presented for 2 or 3 frames (33 or 50 msec). Appropriate durations were determined in pilot tests to provide approximately 65% correct responses. Two durations were used to allow for individual observer differences.

The stimuli were followed by a 1.2^{o} X 1.2^{o} mask (see Figure 1) that remained lit until the observer responded. The mask was constructed by making an outline of the combination of the four stimuli.

To respond, the observer pressed the left, right, up, or down arrow key (numerals 4, 6, 8, or 2, respectively) on the computer keypad to indicate the orientation of the stimulus in the cued position. After the response was entered, feedback of "CORRECT" or "WRONG" appeared at the fixation position and the next trial was initiated.

There were 13 cue-target SOAs, two stimulus durations, three target eccentricities, four cue-target locations (right, left, above, or below fixation), and four stimulus orientations (left, right, up, or down). All of these 1,248 conditions were placed in a separate array for each observer and were presented randomly in blocks of 104 trials each until 1,248 trials were completed. This procedure was repeated 10 times for a total of 12,480 trials per observer.

Because all of the observers had previous experience with this paradigm, no training trials were given. Each observer completed eight blocks of 104 trials each (832 test trials) during each of 15 sessions.

Statistical Analyses

The trials were analyzed with the Hierarchical Log-linear analysis program on a DEC VAX-11/780 system. This analysis program is useful for data that are binary and do not meet the assumptions of parametric tests. This approach provides the same information concerning main effects and interactions as would a fixed effects model analysis of variance (Fienberg, 1980). Because this analysis is a fixed effects model, a separate analysis was computed for each observer as well as for all data combined.

In a Hierarchical Log-linear analysis the data are conceptualized as a multidimensional contingency table with the various factor levels, along with the response variable (correct-incorrect), defining the cells of the contingency table. The multidimensional contingency table is analogous to a two-way contingency table in which a Chi-Square test of independence is often performed to determine the significance of a row by column interaction. In this type of table, the rows represent the independent variables and the columns represent the responses or dependent variables. A significant Chi-Square statistic is evidence that the responses are not distributed identically for each factor. Thus, an interaction of independent variable and the response variable suggests that the independent variable has an effect on the dependent (response) variable. If the observed Chi-Square is very small, then it might be concluded that the independent variable has no effect on (is independent of) the dependent variable. The log-linear model approach (Fienberg, 1980) extends this concept to contingency tables of higher dimensions.

All variables were included as grouping factors for the first analysis: stimulus duration, cue-target SOA, eccentricity, target orientation, location, and observer. Of particular interest was whether or not the various independent variables interacted with the response variable (correct vs. incorrect response). Thus, interactions discussed below all include the accuracy variable in the association. Further interpretations of the various significant interactions were based on additional partial analyses. Inasmuch as effects of target orientation and target location did not provide new information that is relevant to the present hypotheses, they will not be discussed.

Results and Discussion

Discrimination accuracy as a function of SOA and target eccentricity is plotted in Figure 2. These data neither confirm nor disprove the hypothesis that the time required to move attention increases with increases in distance to be moved. If one assumes that the improvement in performance with SOAs of 50 and 67 msec, in comparison to an SOA of 17 msec, was due to the extra time allowed for shift of attention, then there was no delay in the onset of attention effects. On the other hand, there were differences in accuracy as a function of eccentricity for all the longer SOAs. Some of these differences (e.g., differences in asymptotic performance) were anticipated because with full attention, the task was data-limited (Norman & Bobrow, 1975); that is, performance was limited by visual acuity at each eccentricity. However, it is possible that differences in the time used to allocate attention may also have contributed to the observed differences in asymptotic performance.

Statistical analyses revealed significant effects for all variables ($p < .0001$) and many significant interactions. As shown earlier (Cheal et al., 1987; Lyon, 1987), there was a significant increase in proportion correct with an increase in SOA ($X^2[12] = 2491.68$, $p < .0001$). Effects of the precue were found with very brief SOAs. Proportion correct improved with only 33 msec between onset of the precue and onset of the stimulus.

There was also an SOA by eccentricity interaction ($X^2[24] = 103.48$, $p < .0001$). At SOAs of 17, 33, and 50 msec, there were no significant differences for responses to targets at 2^{o}, 6^{o}, or 10^{o}. However, at each SOA from 67 msec to 267 msec, there were significant effects of eccentricity ($p < .0001$). There were also significant differences in asymptote for the three eccentricities (SOA x eccentricity for SOAs from 67 to 268 msec: $X^2[18] = 45.43$, $p < .001$).

Although there were significant effects of duration ($X^2[1] = 734.19$, $p < .0001$), eccentricity by SOA interactions were not affected by duration of the target (duration x SOA x eccentricity interaction: $p = .65$, NS).

The overall eccentricity by SOA interaction was not due to a subset of the observers. Although observers differed ($\underline{X}^2[2] = 415.08$, $\underline{p} < .0001$), there were significant interactions between SOA and eccentricity for each observer (EM: $\underline{X}^2[24] = 172.61$; JB: $\underline{X}^2[24] = 113.46$; SB: $\underline{X}^2[24] = 92.97$, $\underline{p} < .0001$ for each case).

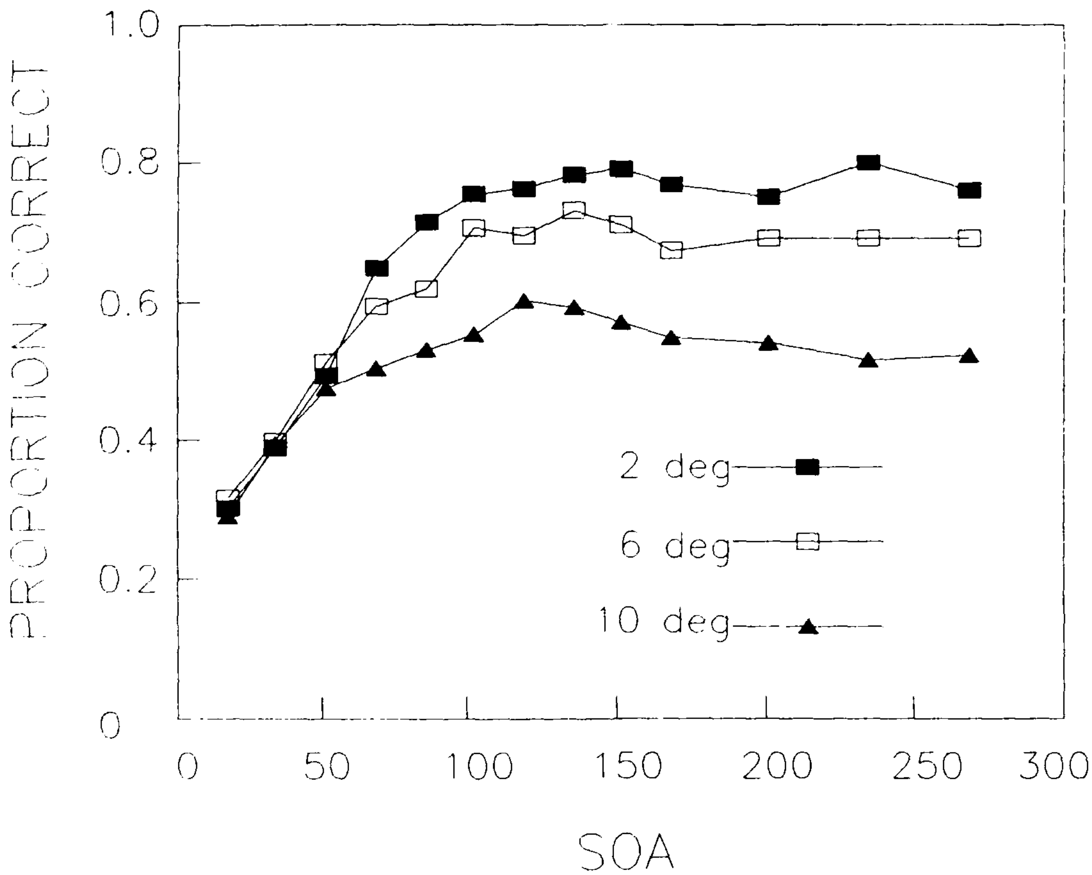

Figure 2. Proportion correct by SOA for Experiment 1. Targets appeared at eccentricities of 2^o, 6^o, and 10^o (peripheral cue). Standard error of the proportion ranged from .013 to .016.

III. EXPERIMENT 2

In Experiment 1, there were no differences in performance as a function of eccentricity at the three shortest SOAs, but there were differences at longer SOAs. In that experiment, attention was manipulated by the use of a peripherally located precue. There are several possible problems with interpretation of data from trials in which the target locations are cued with a peripheral cue. First, it is possible that the cue itself masked the target at the shortest SOAs and, therefore, that the overlap in data from the three eccentricities at short SOAs was due to similar masking in the three conditions. It is also possible that the target masked the cue, causing the observer to respond to a stimulus at an incorrect location on some trials.

Secondly, the time to process the cue and initiate attention movement may differ as a function of eccentricity. Although Tsal (1983) showed that it took no longer to respond to a location cue at 12° than to one at 4°, differences in time for cue processing are a possibility (Eriksen & Murphy, 1987), and this possibility could lead to difficulties in interpreting the results.

It is also possible that attention was not at the fixation bar at the beginning of each trial even though observers were instructed to fixate that location. There is evidence that attention is distributed over the entire display if target and cue are simultaneous (Murphy & Eriksen, 1987). Because it was not possible to have a noninformative cue condition, and we did not have a 0 SOA condition, it is not possible to tell whether performance improved at our shortest SOA.

Therefore, a second experiment was conducted in which a foveal arrow was used as the precue. With a foveal cue, there can be no forward or backward masking between the cue and the target, the problem of possible cue/eccentricity interaction is eliminated, and the observer must attend to the fixation location in order to determine the direction of the arrow. In addition, a 0 SOA condition and a control to determine the efficiency of the mask were included.

Method

Observers

Three women (23 and 24 years of age with normal or corrected to normal vision) participated in this experiment. Two of them (AH and BC) were observers in an earlier study (Cheal et al., 1987) and the other (LE) was naive to visual research.

Procedure

The trials were conducted as in Experiment 1, except that the cue was a foveal arrow of approximately the same size as the targets. The arrow replaced the fixation bar and pointed to one of the four possible target locations. The fixation bar only reappeared in preparation for the next trial after the observer responded. The 13 cue-target SOAs were 0, 17, 33, 50, 67, 84, 100, 117, 134, 150, 167, 200, and 234 msec. All possible trial conditions were randomized as in Experiment 1.

Observers were given one block of practice trials with the targets presented for 320 msec and then a second practice block with the targets presented for 200 msec. These trials were followed by additional practice with the targets presented for 100 msec. This duration was used until the overall proportion correct reached approximately .70 (16, 22, and 27 blocks for AH, BC, and LE, respectively). Then, the experimental trials were begun using target durations of 33 and 50 msec. Each observer completed 8 blocks of 104 trials each for 15 sessions (10 repetitions of each of the 1,248 possible conditions, for a total of 12,480 trials).

Following Experiment 2, observers BC and LE were tested on 30 and 28 blocks (104 trials/block), respectively, on another control condition in order to show the effectiveness of the mask used in these experiments. When no mask was used, observers were able to obtain near-perfect scores. Even with a mask in which more than half of the pixels were turned off, mean accuracy for both observers did not differ from the full mask condition for SOAs of 0 to 117 msec. For longer SOAs, the degraded mask resulted in poorer performance for one observer and better performance for the other in comparison to their normally masked trials. In any case, there is no reason to think that there would be differences in masking effects as a function of eccentricity.

Results and Discussion

As shown in Figure 3, there was little difference in the onset of attention effects for stimuli that were 2° or 6° from fixation. Thus, there was no support at these two eccentricities for the hypothesis that attention takes longer to move a greater distance. However, there was poor performance at all SOAs for 10° eccentricity.

As in Experiment 1, the log-linear model revealed significant main effects of all variables ($p < .0001$) and many significant interactions. In this and subsequent experiments, only statistics relevant to the hypotheses under discussion will be presented. As shown earlier, there was a significant increase in proportion correct as a function of SOA ($X^2[12] = 618.90$, $p < .0001$). This was true for each observer (AH: $X^2[12] = 168.90$; BC: $X^2[12] = 188.05$; LE: $X^2[12] = 330.36$, $p < .0001$).

Individual analyses at each SOA showed that there were significant effects of eccentricity at each SOA ($p < .01$ to $.0001$). However, in separate analyses, the only significant differences found between 2° and 6° eccentricities were those for SOAs of 117 to 167 msec.

There was a slower rate of improvement in accuracy as a function of SOA in Experiment 2 (Figure 3) than in Experiment 1 (Figure 2). This may have been due to the use of the foveal arrow cue in Experiment 2. When a foveal cue is used, determining where to attend is more difficult, may take more time (Jonides, 1981), and/or may use different mechanisms (Briand & Klein, 1987) than does a cue in the target area. Therefore, one might expect more delay in attentional effects with the foveal cue.

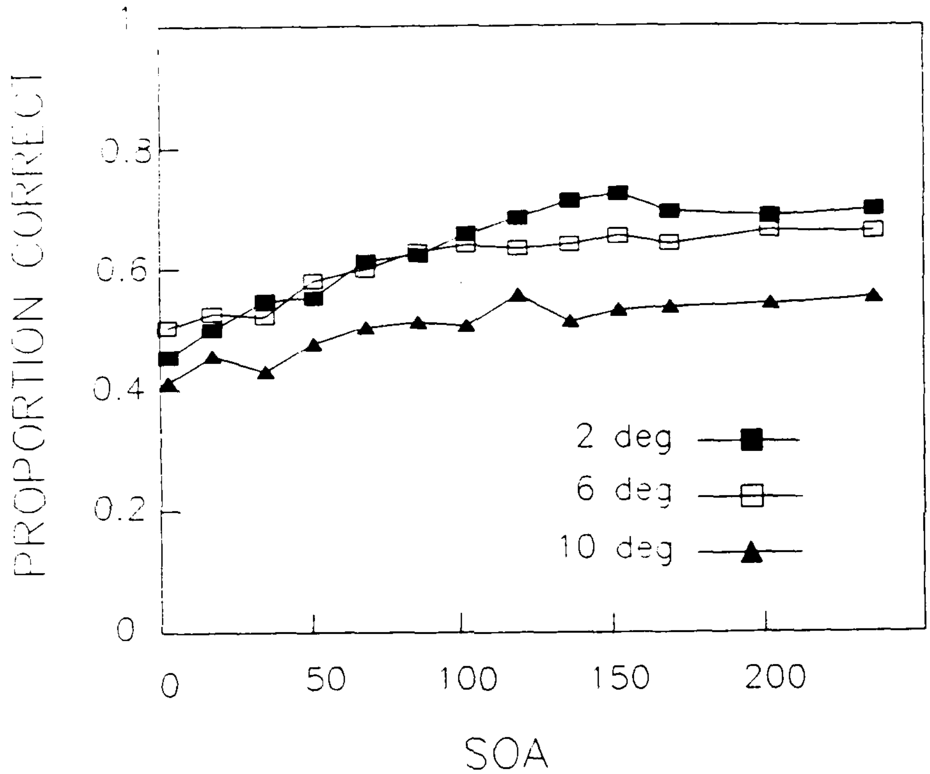

Figure 3. Proportion correct by SOA for Experiment 2. Targets appeared at eccentricities of 2^{o}, 6^{o}, and 10^{o} (foveal cue). Standard error of the proportion varied from .014 to .016.

IV. EXPERIMENT 3

Experiment 2 provided little or no evidence for differences in the time course of attention shifting between 2^{o} and 6^{o} eccentricity, but the results at 10^{o} eccentricity were ambiguous, even for short SOAs. The poor performance at 10° eccentricity could have been due to poor acuity at this eccentricity. It may also have been due to increased uncertainty about target location introduced by the use of the foveal arrow cue. The peripheral cue used in Experiment 1 provided information about both the direction and the eccentricity of the target, but the foveal arrow provided only directional information. Therefore, Experiment 2 was replicated in Experiment 3, but with one change: The three target eccentricities were presented in separate blocks so that eccentricity was known prior to target onset.

Method

Two of the observers from Experiment 2 (BC and LE) were tested in Experiment 3. This experiment replicated Experiment 2 with the exception that each of the three eccentricities was presented in separate blocks of trials. Presentations of the six possible permutations of these three blocks were randomized, with a different order for each day for each observer. All trial conditions except eccentricity were randomized as in Experiment 1.

No training was required. At each session, observers were tested on two blocks (LE) or three blocks (BC) of 104 trials each for each of the three eccentricities. Each observer had a total of 24 blocks at each eccentricity (72 blocks at 104 trials per block = 7,488 trials).

Results and Discussion

The data from Experiment 3 (Figure 4) clearly replicated the data from Experiment 2 (Figure 3). Presenting the eccentricities in separate blocks did not change the differences in the SOA curves. Although accuracy was improved in Experiment 3 in comparison to Experiment 2, this was probably due to the additional practice given these observers.

The log-linear model again revealed significant main effects of all variables ($p < .0001$). There was a significant increase in accuracy as a function of SOA both for the group data ($X^2[12] = 414.76$) and for each observer (BC: $X^2[12] = 172.09$; LE: $X^2[12] = 227.71$; each $p < .0001$).

Individual analyses for each SOA showed significant effects of eccentricity at each SOA from 17 to 234 msec (p from $< .05$ to $< .0001$). When the cue and target were presented simultaneously, the main effect of eccentricity did not reach significance ($X^2[2] = 5.78$, $p < .056$).

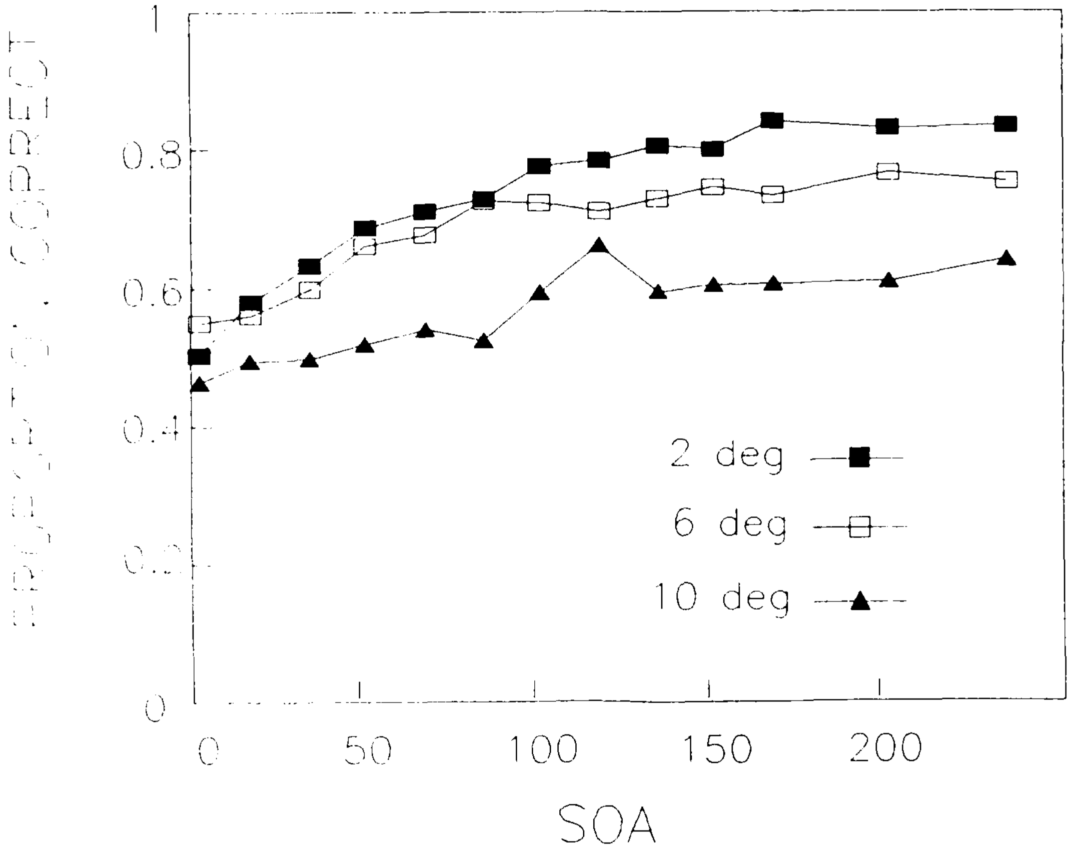

Figure 4. Proportion correct by SOA for Experiment 3. Targets appeared in separate blocks at eccentricities of 2^o, 6^o, and 10^o (foveal cue). Standard error of the proportion varied from .019 to .026.

In a separate analysis for 2^o and 6^o eccentricities, there were no significant differences for SOAs from 0 to 100 msec. However, there were significant differences at SOAs from 117 to 234 msec (p = .001 to .02, except at 150 msec SOA where $p < .07$). Thus, the data from 2^o and 6^o eccentricities do not support the hypothesis that time to move attention increased with increased distance. On the other hand, the 10^o eccentricity data were ambiguous.

V. EXPERIMENT 4

The data from the first three experiments suggest that no more time is needed for attention to move to targets at 6^o than to targets at 2^o. This conclusion is, of course, based on a number of assumptions. One is that the increase in accuracy with longer SOAs represents the onset of attention effects. Another possible interpretation of Experiment 1, that performance at the shortest SOAs could have been reduced by masking of the target by the cue, and/or masking of the cue by the target, was eliminated in Experiments 2 and 3 by using a central arrow cue. However, use of a foveal cue adds other problems. At the least, another process is added to each trial; i.e., the observer must process the arrow in order to determine the direction in which to shift attention (Jonides, 1981). It is even possible that peripheral and foveal cuing induce functionally different processes (Briand & Klein, 1987). Comparison of Figure 2 with Figures 3 and 4 shows that precuing effects developed more slowly with the foveal cue than with the peripheral cue. This delay was also found in previous experiments using this paradigm (Lyon, 1987).

A further complication in these experiments is the poor performance for discrimination of targets at 10° eccentricity. Even after considerable practice (nearly 20,000 trials), there was only a 14% increase in accuracy at asymptote (SOAs from 117 msec to 134 msec) than at 0 msec SOA for 10° stimuli, whereas there was a 43% improvement with long SOAs for 2° stimuli. It is tempting to assume that differences in asymptote for different eccentricities were due to differences in acuity. There is abundant evidence that vision is poorer at locations further from fixation. Thus, this poor performance could be due to the increased difficulty of the task at 10° eccentricity.

This possibility was tested by scaling the targets in order to equate their discriminability. Human visual discrimination performance has been shown to vary with the cortical magnification factor (the cell density in cortical locations that correspond to locations in the visual field; see Cowey & Rolls, 1974; Rovamo & Virsu, 1979). Therefore, two additional experiments were conducted using the same paradigm that was used in the first three experiments, but the stimuli at each eccentricity were scaled according to the cortical magnification factor.

Method

Observers

Three right-handed observers (1 man and 2 women, 25 to 30 years of age, with normal vision) were paid to participate in 11 to 15 approximately 1-hour sessions.

Stimuli

As in the previous experiments, T-like figures were used. In this experiment, however, the stimuli varied in size depending on the distance and the direction from fixation according to the cortical magnification factor (CMF). Using the formulae of Rovamo and Virsu (1979) and substituting 2^o, 6^o, and 10^o E (eccentricity), four magnification factors (M^{-1}) were computed for each of the three eccentricities. Because trials were conducted binocularly, the mean of the nasal and temporal magnification factors was used to create the stimuli to be presented on the right and on the left. Inferior and superior magnification factors were very similar in value; therefore, the mean of these values was used for calculating the sizes of stimuli to be presented above or below fixation. The stimuli used in the first three experiments were considered to be appropriate for 6^o nasal/temporal with a magnification factor of .30 (Table 1). The other five target sizes were based on the ratio between their individual magnification factors and .30. For example: .30:12 = .44:x. In this case, x = 17.6, which was truncated to 17 for the corresponding proportion for 6^o superior/inferior stimuli.

Cues for 2^o and 6^o eccentricities were a rectangle of the same dimensions as those of the composite stimuli for that location. Because the cue and target appeared on the screen simultaneously for trials with 0 SOA, the cues for 10^o had to be smaller than the stimuli in order to fit both on the computer screen without overlap.

A pretest was conducted in order to determine whether the stimuli were equally visible at all eccentricities. Three observers were tested in three to five sessions each. In each session there were 12 blocks of 80 trials per block. There was no precue, and targets always appeared in a fixed location within a block. Presentation order of the 12 blocks, each testing a different location, was randomized separately for each session for each observer. Large individual variability was found in the differences in proportion correct between eccentricities (9%, 14%, and 21%, for observers NR, JB, and EM, respectively). Furthermore, the relative magnitude of proportion correct for each eccentricity varied among different observers. For instance, for JB, 6^o was best, then 10^o, then 2^o. Part of this variability among observers could be due to correction for myopia in one of them (14% difference) and to possible small losses in peripheral vision due to age (40 years) in another observer (21% difference). Therefore, young observers with normal uncorrected vision were chosen for this experiment.

Table 1. Sizes of Stimuli for Experiments 4 and 5

	M^{-1a}	Pixels[b]	Targets[c]	Cues[d]
2^{o} N/T[e]	.20	5 x 7	$.45^{o}$	$.45^{o}$
2^{o} S/I	.23	5 x 9	$.6^{o}$	$.6^{o}$
6^{o} N/T	.30	7 x 12	$.9^{o}$	$.9^{o}$
6^{o} S/I	.44	10 x 17	1.2^{o}	1.2^{o}
10^{o} N/T	.52	12 x 21	1.5^{o}	1.2^{o}
10^{o} S/I	.66	15 x 26	1.8^{o}	1.2^{o}

[a]M^{-1} is the magnification factor calculated according to Rovamo and Virsu, 1979.

[b]The number of pixels represent a + sign that is a composite of 4 orientations of the target.

[c]Sizes in degrees are given for a symmetrical + sign that is a composite of 4 orientations of the target. In each case, the mask was an outline of the composite of the appropriate size.

[d]Sizes in degrees are for one side of a square cue.

[e]Sizes were computed separately for nasal/temporal (N/T) and superior/inferior (S/I) target locations.

Procedure

The procedure was the same as that used in Experiment 1 with peripheral cues. The 13 SOAs used were 0, 16.7, 33, 50, 67, 84, 100, 117, 134, 150, 167, 200, and 234 msec. As previously, stimuli (durations of 33 and 50 msec) appeared at each of the four locations (above, below, right, and left of fixation) following the SOA. These four stimuli could appear at approximately 2^{o}, 6^{o}, or 10^{o}, dependent on whether the cue was at approximately 3^{o}, 7^{o}, or 11^{o}, respectively. The target was the stimulus that was adjacent to the location that was cued. All 1248 possible conditions (3 eccentricities, 2 targets, 4 target locations, 4 target orientations, and 13 SOAs) were randomized as in Experiment 1.

The stimuli were followed by a mask that was sized according to the stimuli that were presented. Each mask was constructed of an outline of the combination of the four possible stimulus orientations. The mask remained lit until the observer responded.

For training, observers were given blocks of trials starting with stimulus durations of 500 or 320 msec, and then durations decreasing to 100 msec. When observers responded with at least 70% accuracy (3, 3, and 16 blocks, for ET, LF, and GN, respectively), stimuli durations were reduced to 33 and 50 msec. Each observer completed a total of 96 blocks (104 trials each; 9,984 test trials) at durations of 33 and 50 msec.

Results and Discussion

The data from Experiment 4 were consistent with the data from the earlier experiments. Again there was no lateral translation of the accuracy/SOA function due to eccentricity (Figure 5). In fact, when the targets were sized according to CMF, there was little difference in accuracy between the three eccentricities except at the longest SOAs. The significant effect of eccentricity ($\underline{X}^2[2] = 22.20$, $\underline{p} < .0001$) was due to poor performance at long SOAs for 10° targets (eccentricity x SOA interaction: $\underline{X}^2[24] = 75.63$, $\underline{p} < .0001$; eccentricity was not significant for 2° and 6° targets, $\underline{p} = .11$). There were no significant effects of eccentricity for SOAs from 0 to 134 msec ($\underline{p} = .91$).

The significant effects of eccentricity at long SOAs (150 to 234 msec SOA: $\underline{X}^2[2] = 63.28$, $\underline{p} < .0001$) is partially explained by relative differences between eccentricities for different observers. Performance was poorest for 10° targets for observer ET (Figure 6) and observer GN (Figure 7), but there was no effect of eccentricity for observer LF ($\underline{p} = .46$, Figure 8). These differences between observers were reflected in an interaction between observers and eccentricity ($\underline{X}^2[4] = 60.56$, $\underline{p} < .0001$).

VI. EXPERIMENT 5

As a further test of the assumption that the rise in the accuracy/SOA curve was due to the additional time used to focus attention and was not due to masking interactions of the target and cue, a fifth experiment was conducted. In this experiment, trials were presented as in Experiment 4, with the exception that a foveal arrow cue was used.

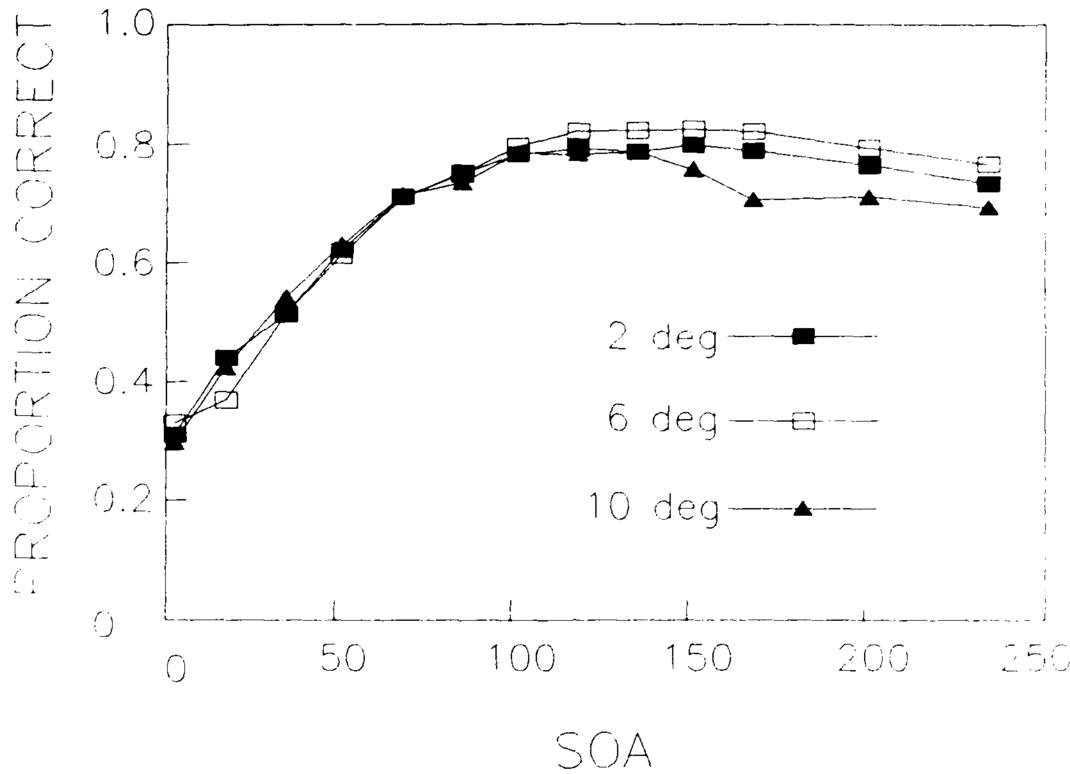

Figure 5. Proportion correct by SOA for Experiment 4. Targets, sized according to CMF, were located at eccentricities of 2°, 6°, and 10° (peripheral cue). The standard error of the proportion varied from .014 to .018.

As shown in Experiments 3 and 4, effects of a foveal precue developed more slowly than did peripheral precue effects. Results of a previous study suggested that extensive practice could reduce the size of this difference. If so, then perhaps the size of the eccentricity by SOA interaction might also change after extensive practice. To test this possibility, one of the observers was tested on an additional 12,480 trials.

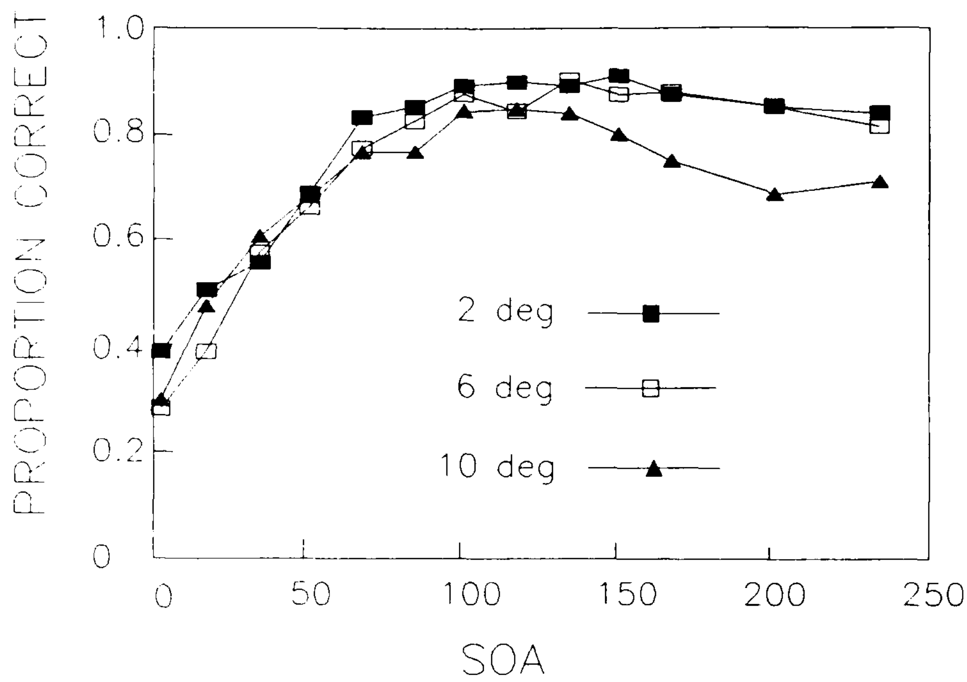

Figure 6. Proportion correct by SOA for observer ET. Targets, sized according to CMF, were located at eccentricities of 2^{o}, 6^{o}, and 10^{o} (peripheral cue).

Method

The two women observers tested in Experiment 4 were used. The only difference between Experiments 4 and 5 was the replacement of the peripheral square cue with a foveal arrow cue as in Experiments 2 and 3. Stimuli were sized according to the CMF as in Experiment 4 (Table 1). All variable conditions were randomized as in Experiment 1.

Practice trials were given as in Experiment 4 until responses were about 65% accurate at 100 msec duration (11 and 5 blocks for ET and LF, respectively). One observer (LF) was then tested on 120 blocks of 104 trials each with stimulus durations of 33 and 50 msec (12,480 trials in 15 sessions) whereas the other observer (ET) was tested on 240 blocks of 104 trials each (24,960 trials in 30 sessions). The additional trials were given to ET in order to see whether the slope of the accuracy/SOA curve would change with continued practice.

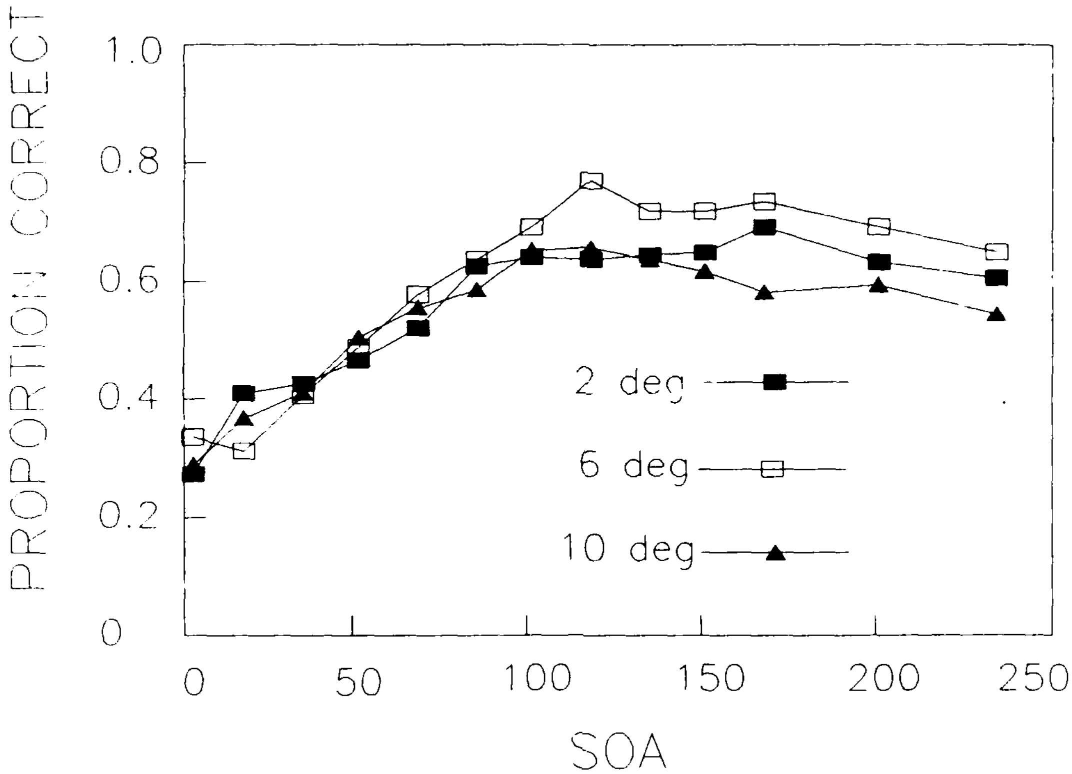

Figure 7. Proportion correct by SOA for observer GN. Targets, sized according to CMF, were located at eccentricities of 2°, 6°, and 10° from fixation (peripheral cue).

Results and Discussion

The results of this experiment were consistent with those of Experiments 1 through 4, in that there was no lateral translation of the accuracy/SOA function with increasing eccentricity (Figure 9). There was a significant effect of eccentricity ($X^2[2] = 81.37$, $p < .0001$), but in this experiment, unlike the first four experiments, there was no eccentricity by SOA interaction. In fact, the effect of eccentricity was due to poorer performance for the 2° targets than for 6° or 10° targets. This is the opposite of what one would expect if time to move attention increased with increased distance.

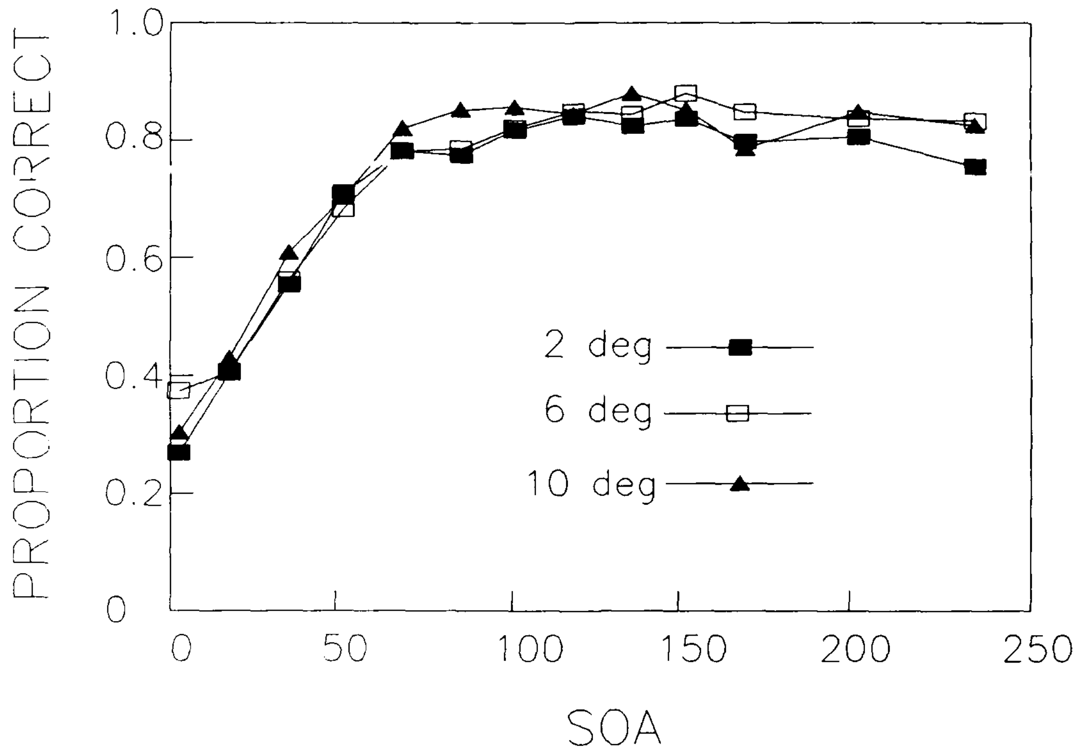

Figure 8. Proportion correct by SOA for observer LF. Targets, sized according to CMF, were located at eccentricities of 2°, 6°, and 10° (peripheral cue).

The small differences due to eccentricity in these data were not consistent for the two observers (observer x eccentricity interaction: $\underline{X}^2[2] = 57.58$, $\underline{p} < .0001$). For observer ET, proportion correct was .67, .69, and .67 for 2°, 6°, and 10° targets, respectively (eccentricity effect: $\underline{X}^2[2] = 15.79$, $\underline{p} < .001$), whereas for observer LF, proportion correct was .65, .72, and .74 at these eccentricities (eccentricity effect: $\underline{X}^2[2] = 110.83$, $\underline{p} < .0001$). Thus, performance was best for 6° targets for observer ET and for 10° targets for observer LF, neither of which would be predicted if attention moved at a fixed velocity. In light of the individual differences that were found when the stimuli were tested at different locations in separate blocks (described in the Stimuli section in Methods of Experiment 4), it is likely that differences in asymptotic performance in Experiments 4 and 5 were due to individual variability in relative sensitivity as a function of eccentricity.

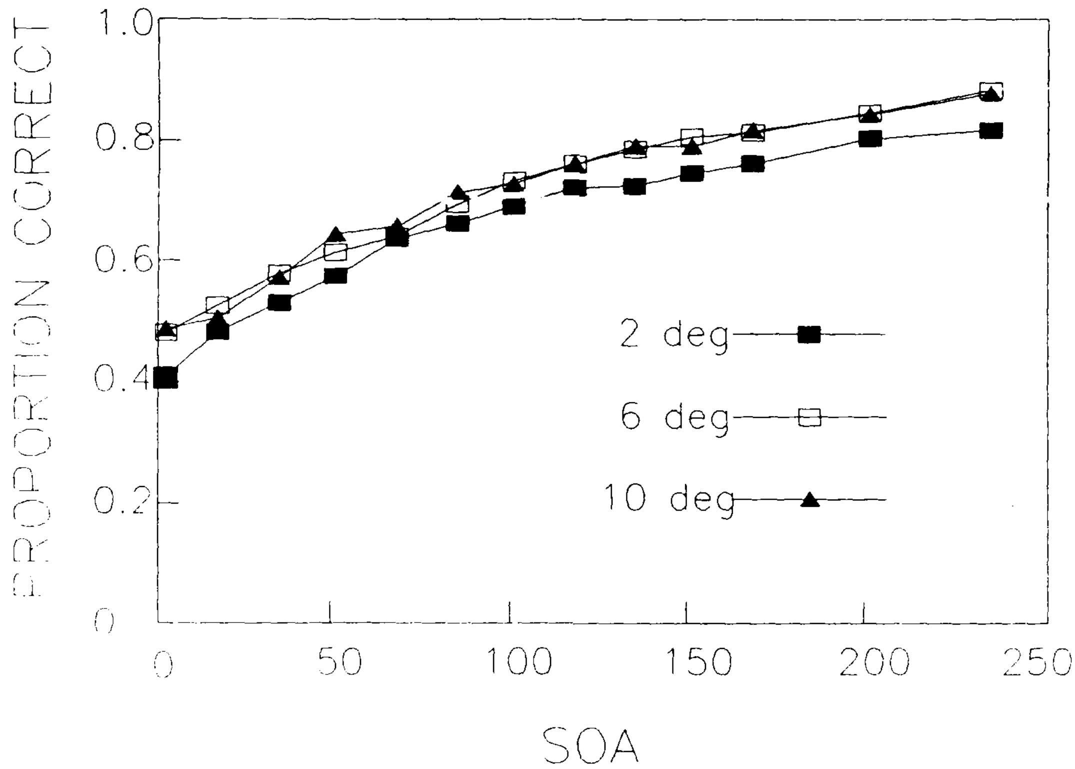

Figure 9. Proportion correct by SOA for Experiment 5. Targets, sized according to CMF, were located at eccentricities of 2^{o}, 6^{o}, and 10^{o} (foveal arrow cue). Standard error of the proportion varied from .010 to .016.

Practice increased the amount of improvement as a function of SOA but did not eliminate the slower increase in accuracy with SOA that was found when a foveal arrow precue was used. Data from Experiment 2 (Figure 3), Experiment 3 (Figure 4), and Experiment 5 (Figure 9) were consistent in that there was a more gradual increase in accuracy with SOA when a foveal arrow cue was used than when a peripheral precue was used, as in Experiment 1 (Figure 2) or Experiment 4 (Figure 5). Performance improved with practice for both observers in Experiment 5 as shown by a significant increase between the first group of 6,240 trials and the second group of 6,240 trials ($X^2[1] = 407.99$, $p < .0001$). The improvement for observer ET across four groups of 6,240 trials each is shown in Figure 10. She improved approximately 10 percentage points over each group of trials (.535, .634, .731, .799 overall proportion correct; $X^2[1] = 271.81$, $p < .0001$; the smaller increase by the fourth group may have been due to a ceiling effect at the longest SOAs). Improvement on the part of each observer, however, did not affect the SOA by eccentricity interaction (SOA x eccentricity x trial group interaction was NS, $p = .76$ and $p = .97$ for ET and LF, respectively). Thus, even when ET was near ceiling for the long SOAs, there was still a slower rise in accuracy in comparison to her earlier trials with a peripheral cue (Figure 6).

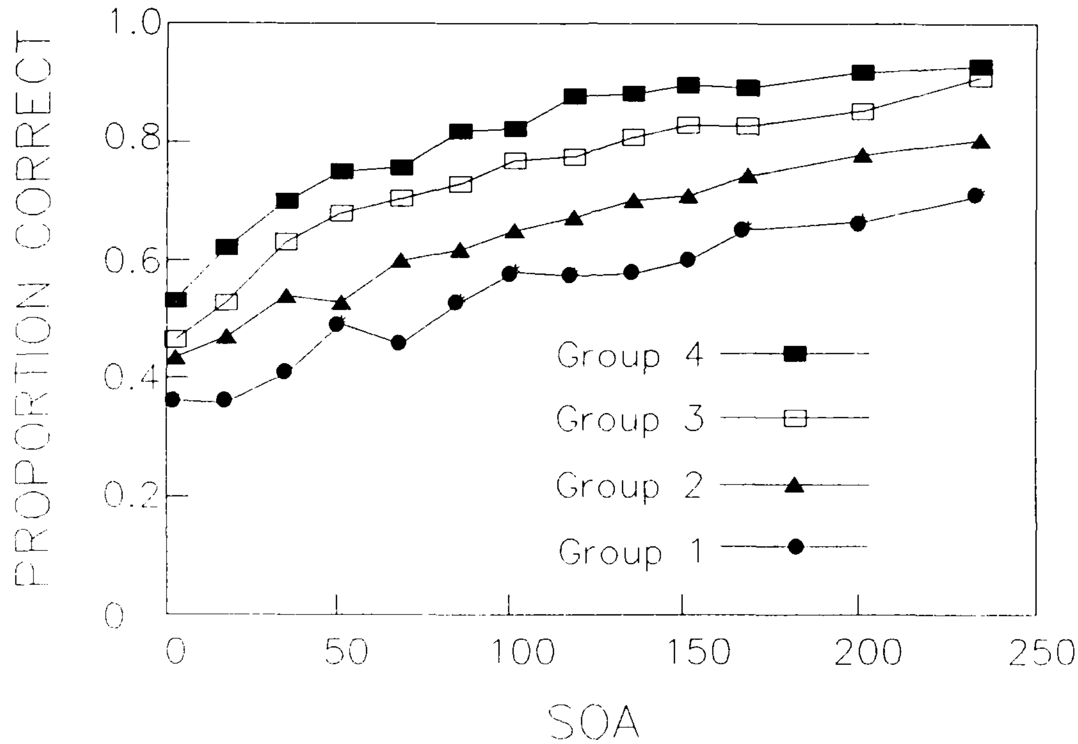

Figure 10. Practice effects for observer ET. Proportion correct as a function of SOA for successive groups of 6,240 trials for observer ET in Experiment 5 (foveal arrow cue). Each line is the mean for three eccentricities and two target durations.

VII. GENERAL DISCUSSION

The present experiments do not support the hypothesis that the time to move attention increases with increases in distance to be moved. The metaphor that attention moves through visual space like a spotlight suggested that there would be a delay in the onset of precue effects with increasing target eccentricity.

The predicted size of the delay was estimated from Tsal (1983) to be 16.7 msec for each 4^{o} of target eccentricity. Clearly, that prediction was not supported by our data. Generally, like the work of Murphy and Eriksen (1987), the present research provides evidence against the analog movement of attention model.

Instead, the data suggest that the time required for attentional movement is independent of distance, up to 10^{o}. There was no consistent shift in the accuracy/SOA function with increasing eccentricity, whether the targets were precued with a peripheral rectangle or with a foveal arrow. These results were highly reliable. In each experiment, the curves for the three eccentricities did not differ at short SOAs.

Although there were large differences in asymptotic performance as a function of eccentricity in Experiments 1, 2, and 3, the data from Experiments 4 and 5 suggest that these differences were due to differences in the visibility of the targets rather than to the time needed to shift attention. When targets were scaled according to CMF in order to equate their visibility at different eccentricities, there were few differences in asymptotic performance and even these small differences were not consistently in the direction predicted by the hypothesis of a fixed velocity of attention.

The conclusion that time to shift attention does not depend on distance (up to 10^{o}) is, of course, based on the assumption that attention is responsible for the observed improvement in performance with increasing SOA. In order to make that assumption, a number of controls were included in the research design:

1. In order to control the location of attention prior to a shift in attention, a central precue was used in some experiments. In these cases, attentional focus on the foveal arrow would be required in order to determine at which of the four locations the target would appear.

2. Cues were always valid so that there would be no advantage in spreading attentional resources to locations other than the target location, and performance would be facilitated (Shaw, 1978; Shaw & Shaw, 1977).

3. In order to plot a complete time course of attentional effects, 13 different SOAs were used. These included very short SOAs as well as SOAs that were long enough to establish asymptotic performance.

4. Eye movements could not account for the results, since eyes were monitored and most trials were too brief to allow a saccade to the target.

5. Four stimuli appeared on the target screen so that the target appearing alone would not elicit attention to that location (Jonides, 1981).

6. In order to control the total time for a shift of attention, target durations were short and targets were immediately followed by a mask.

7. In some of the experiments, the size of the targets was equated for visibility at different eccentricities in order to control for effects due to differences in visibility.

In addition to the seven controls listed above, it was also necessary to show that the accuracy/SOA curve was not the result of masking interactions between the target and the cue. In three experiments, it was shown that results obtained with a foveal cue were similar to those obtained with a peripheral cue. With a foveal cue, the target could not mask or be masked by the cue. The only important difference between the data from experiments with a foveal cue and those from experiments with a peripheral cue was the slower rate of improvement in performance as a function of SOA with the foveal cue.

It is also unlikely that an alerting effect of the cue was responsible for the observed improvement in performance. As stated in the introduction, warning signal effects were minimized in the design of the experiments. Even if there were small warning signal effects, there is no reason to expect differences in these effects due to target eccentricity. Moreover, even differential alerting effects at different eccentricities would not explain both the presence of differences in asymptote when the stimuli were the same size at different eccentricities, and the absence of such differences when the stimuli were scaled for CMF.

It was also shown that although there were clear practice effects (Figure 10), practice changed neither the shape of the accuracy/SOA function nor the interaction of SOA and eccentricity.

Thus, the effects reported here appear to be spatial attention effects that are not well described by a fixed-velocity moving spotlight metaphor. A more accurate metaphor may be that of a zoom lens (Eriksen & Yeh, 1985) in which the attentional field can contract as necessary in order to extract information from the target. This latter model accounts for the fact that attention allocation varies according to the task. Humphreys (1981) showed that the width of the attentional field could be modified according to the location of the target relative to fixation. Later, LaBerge (1983) demonstrated that it was possible to focus narrowly on a single letter, or more widely over the area of a word. These data were consistent with a two-process model in which attention could be distributed over the visual field or focused narrowly on a particular location (Jonides, 1983). In the zoom lens model of Eriksen and Yeh (1985), however, attention is thought to function on a continuum from distributed to focused attention.

Another current model is that of an attentional filter gradient that can assume different shapes (LaBerge & Brown, in press). According to this model, attention can be spread across the visual field, and a filter receives input from higher processes to facilitate the ability to extract information from a specifically cued location. The gradient may develop at a new location as needed. This model may explain how attention can be allocated to a ring (Egly & Homa, 1984) or to noncontiguous areas (Müller & Findlay, 1987). It is also possible that the filter could receive information to facilitate processing of a specific category, such as the facilitation due to foreknowledge of the target category (e.g., whether it will be a letter or a digit; Lambert, 1987).

Thus, other models for the allocation of visual attention have been developed in recent years. These models are in some ways similar to the spotlight model, but they do not incorporate the idea that the focus of attention takes time to move across visual space. Our results argue that the fixed velocity movement of a spotlight may not be a useful property for models of attention.

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